arXiv:0812.0795v1 [astro-ph] 3 Dec 2008

Section on Prospects for Dark Matter Detection of the White Paper on the Status and Future of Ground-Based TeV Gamma-Ray Astronomy

J. Buckley (Wash. University in St. Louis, Physics Department and McDonnell Center for the Space Sciences), E.A. Baltz (KIPAC, Stanford University), G. Bertone (Institut d'Astrophysique de Paris, Universit Pierre et Marie Curie), K. Byrum (Argonne National Laboratory), B. Dingus (Los Alamos National Laboratory), S. Fegan (University of California, Los Angeles), F. Ferrer (Wash. University in St. Louis, Physics Department and McDonnell Center for the Space Sciences), P. Gondolo (The University of Utah), J. Hall (Fermi National Accelerator Laboratory), D. Hooper (Fermi National Accelerator Laboratory), D. Horan (Argonne National Laboratory), S. Koushiappas (Brown University), H. Krawczynski (Wash. University in St. Louis, Physics Department and McDonnell Center for the Space Sciences), S. LeBohec (The University of Utah), M. Pohl (Iowa State University), S. Profumo (University of California, Santa Cruz), J. Silk (Oxford University), T. Tait (Argonne National Laboratory and Northwestern University), V. Vassiliev (University of California, Los Angeles) R. Wagner (Argonne National Laboratory), S. Wakely (The University of Chicago), M. Wood (University of California, Los Angeles), and G. Zaharijas (Argonne National Laboratory)

ABSTRACT

This is a report on the findings of the dark matter science working group for the white paper on the status and future of TeV gamma-ray astronomy. The white paper was commissioned by the American Physical Society, and the full white paper can be found on astro-ph (arXiv:0810.0444). This detailed section discusses the prospects for dark matter detection with future gamma-ray experiments, and the complementarity of gamma-ray measurements with other indirect, direct or accelerator-based searches. We conclude that any comprehensive search for dark matter should include gamma-ray observations, both to identify the dark matter particle (through the characteristics of the gamma-ray spectrum) and to measure the distribution of dark matter in galactic halos.

1. Introduction

In the last decade, a standard cosmological picture of the universe (the ΛCDM cosmology) has emerged, including a detailed breakdown of the main constituents of the energy-density of the universe. This theoretical framework is now on a firm empirical footing, given the remarkable agreement of a diverse set of astrophysical data (1; 2). In the ΛCDM paradigm, the universe is spatially flat and its energy budget is balanced with $\sim$4% baryonic matter, $\sim$26% cold dark matter (CDM) and roughly 70% dark energy.

While the dark matter has not been directly detected in laboratory experiments, the gravitational effects of dark matter have been observed in the Universe on all spatial scales, ranging from the inner kiloparsecs of galaxies out to the Hubble radius. The Dark Matter (DM) paradigm was first introduced by Zwicky (4) in the 1930s to explain the anomalous velocity dispersion in galaxy clusters.

In 1973, Cowsik and McClelland (5) proposed that weakly-interacting massive neutrinos could provide the missing dark matter needed to explain the virial mass discrepancy in the Coma cluster. However, since neutrinos would be relativistic at the time of decoupling, they would have a large free-streaming length. While neutrino dark matter would provide an explanation for structure on the scale of clusters, this idea could not explain the early formation of compact halos that appear

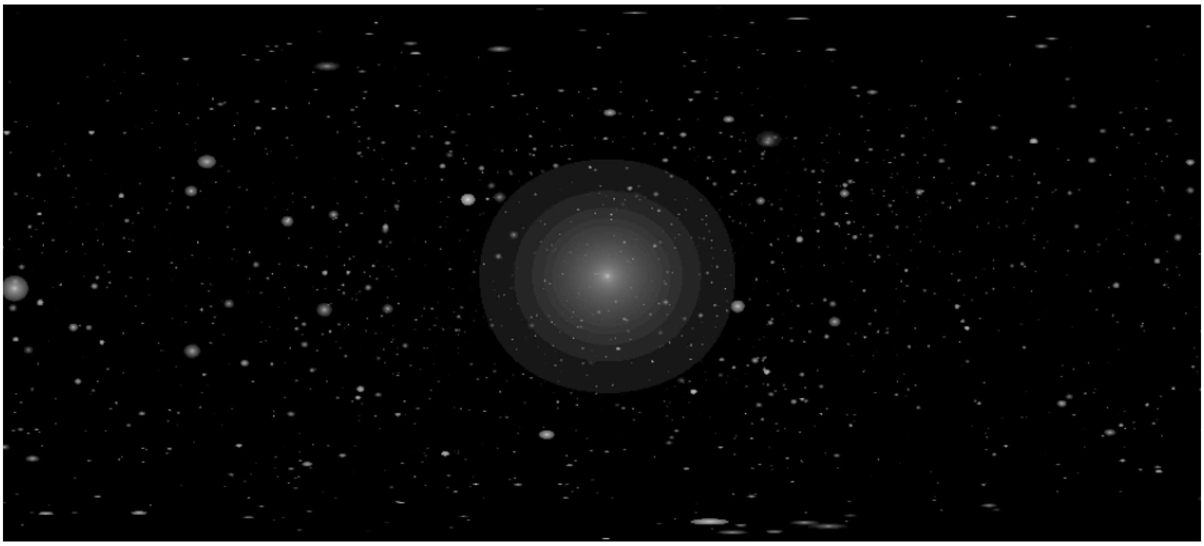

Fig. 1.—: Simulated appearance of the gamma-ray sky from neutralino annihilation in the galactic halo plotted as the intensity in galactic coordinates (3). The galactic center appears as the bright object at the center of the field of view. If the sensitivity of a future ACT experiment were high enough, a number of the other galactic substructures visible in this figure could be detected with a ground-based gamma-ray experiment.

to have seeded the growth of smaller structures, such as galaxies.

This observation motivated the concept of cold dark matter (CDM) consisting of weakly interacting massive particles (WIMPs) with rest energy on the order of 100 GeV that were nonrelativistic (cold) at the time of decoupling. CDM would first form very small, dense structures that coalesced into progressively larger objects (galactic substructure, galaxies, then galaxy clusters and superclusters) in a bottom-up scenario known as hierarchical structure formation. A plethora of diverse observations suggests the presence of this mysterious matter: gravitational lensing, the rotation curves of galaxies, measurements of the cosmic microwave background (CMB), and maps of the large-scale structure of galaxies.

Measurements of the CMB have been the key to pinning down the cosmological parameters; the angular distribution of temperature variations in the CMB depends on the power spectrum of fluctuations produced in the inflationary epoch and subsequent acoustic oscillations that resulted from the interplay of gravitational collapse and radiation pressure. These acoustic peaks contain information about the curvature and expansion history of the universe, as well as the relative contributions of baryonic matter, dark matter and dark energy. Combined with measurements of the large-scale distribution of galaxies, as mapped by the Sloan Digital Sky Survey (SDSS) and the 2dF Galaxy Redshift survey, these data can be well described by models based on single field inflation.

Observations of galactic clusters continue to be of central importance in understanding the dark matter problem. Recent compelling evidence for the existence of particle dark matter comes from the analysis of a unique cluster merger event 1E0657-558 (6). Chandra observations reveal that the distribution of the X-ray emitting plasma, the dominant component of the visible baryonic matter, appears to be spatially segregated from the gravitational mass (revealed by weak lensing data). This result provides strong evidence in favor of a weakly-interacting-particle dark matter, while contradicting other explanations, such as modified gravity.

The primordial abundances of different particle species in the Universe are determined by assuming that dark matter particles and all other particle species are in thermal equilibrium until the expansion rate of the Universe dilutes their individual reaction rates. Under this assumption (which provides stunningly accurate estimates of the abundance of light elements and standard-model particles), particles that interact weakly fall out of equilibrium sooner, escaping Boltzmann suppression as the temperature drops, and hence have larger relic abundances in the current universe. While a weakly-interacting thermal relic provides an appealing and well-constrained candidate for the dark matter, nonthermal relics such as axions or gravitinos, resulting from the decay of other relics, can also provide contributions to the total matter density or even provide the dominant component of the dark matter. Just as there is an unseen component of the universe required by astrophysical observations, there are compelling theoretical arguments for the existence of new particle degrees of freedom in the TeV to Planck scale energy range. In particle physics, a solution to the so-called hierarchy problem (the question of why the expected mass of the Higgs particle is so low) requires new physics. An example is provided by supersymmetry, a symmetry in nature between Fermions and bosons, where the supersymmetric partners of standard model particles lead to cancellations in the radiative corrections to the Higgs mass. The hierarchy problem in particle physics motivates the existence of new particle degrees of freedom in the mass range of 100 GeV to TeV scale. It is a remarkable coincidence that if dark matter is composed of a weakly interacting elementary particle with an approximate mass of this order (i.e., on the scale of the weak gauge bosons $\sim$ 100 GeV), one could naturally produce the required cosmological density through thermal decoupling of the DM component. To make a viable candidate for the dark matter, one more ingredient is required; the decay of such a particle must be forbidden by some conserved quantity associated with an, as yet, undiscovered symmetry of Nature so that the lifetime of the particle is longer than the Hubble time.

In supersymmetry, if one postulates a conserved quantity arising from some new symmetry (R-parity), the lightest supersymmetric particle (LSP) is stable and would provide a natural candidate for the dark matter. In fact, R-parity conservation is introduced into supersymmetry not to solve the dark matter problem, but rather to ensure the stability of the proton. In many regions of supersymmetric parameter space, the LSP is the neutralino, a Majorana particle (its own antiparticle) that is the lightest super-symmetric partner to the electroweak and Higgs bosons.

For a subset of the supersymmetric parameter space, these particles could be within the reach of experimental testing at the Large Hadron Collider (LHC) (if the rest mass is below about 500 GeV) (7) or current or future direct detection experiments XENON-I,II (8), GENIUS (10; 9) ZEPLIN-II,III,IV (11), SuperCDMS(12), and EDELWEISS-I,II(14) (if the nuclear recoil cross-section is sufficiently large). While it is possible that the LHC will provide evidence for supersymmetry, or that future direct detection experiments will detect a clear signature of nuclear-recoil events produced by dark matter in the local halo, *gamma-ray observations provide the only avenue for measuring the dark matter halo profiles and illuminating the role of dark matter in structure formation.*

Neutralinos could also be observed through other indirect astrophysical experiments searching for by-products of the annihilation of the lightest supersymmetric particle, such as positrons, low-energy antiprotons, and high-energy neutrinos. Since positrons and antiprotons are charged particles, their propagation in the galaxy suffers scattering off of the irregular inter-stellar magnetic field and hides their origin. Electrons with energy above $\sim$10 GeV suffer severe energy losses due to synchrotron and inverse-Compton radiation, limiting their range to much less than the distance between Earth and the galactic center. However, cosmic-ray observations could provide evidence for local galactic substructure through characteristic distortions in the energy spectra of these particles. Detection of electrons from dark matter annihilation thus depend critically on large uncertainties in the clumpiness of the local halo. Neutrinos would not suffer these difficulties and, like photons, would point back to their sources. But given the very low detection cross section compared with gamma-rays, the effective area for a $\sim$km^3 neutrino experiment is many orders of magnitude smaller than for a typical ground-based gamma-ray experiment. While detection of neutrinos directly from discrete sources (e.g., the Galactic center) would be difficult for the current generation of neutrino detectors there is a reasonable prospect for detection of neutrinos from WIMPs s in the local halo that are captured by interactions with the earth or sun where they might have sufficient density to give an observable neutrino signal. Compared with all other detection techniques (direct and indirect), γ-ray measurements of dark-matter are unique in going beyond a detection of the local halo to providing a measurement of the actual distribution of dark matter on the sky. Such measurements are needed to understand the nature of the dominant gravitational component of our own Galaxy, and the role of dark matter in the formation of structure in the Universe.

In other regions of supersymmetric parameter space, the dark matter particle could be in the form of a heavy scalar like the sneutrino, or Rarita-Schwinger particles like the gravitino. In general, for gravitino models, R-parity need not be conserved and gravitinos could decay very slowly (with a lifetime on the order of the age of the universe) but could still be visible in gamma-rays (15). Supersymmetry is not the only extension to the standard model of particle physics that provides a dark matter candidate, and there is no guarantee that even if supersymmetry is discovered it will provide a new particle that solves the dark matter problem. Other extensions of the standard model involving TeV-scale extra dimensions, include new particles in the form of Kaluza-Klein partners of ordinary standard-model particles. The lightest Kaluza-Klein particle (LKP) could be stable and hence provide a candidate for the dark matter if one invokes an absolute symmetry (KK parity conservation) resulting from momentum conservation along the extra dimension. The mass of the lightest Kaluza-Klein particle (e.g, the $B^{(1)}$ particle corresponding to the first excitation of the weak hypercharge boson) is related to the physical length scale of the extra dimension and could be on the TeV-scale (but not much smaller) and provide a viable CDM candidate. The $B^{(1)}$ is expected to annihilate mainly to quarks or charged leptons accompanied by an internal bremsstrahlung photon by the process $B^{(1)} + B^{(1)} \to l^+ + l^- + \gamma$ (16). The high energy of the LKP ($\gtrsim 1$ TeV), and very-hard spectrum gamma-ray production make ground-based gamma-ray and high-energy cosmic-ray electron measurements promising avenues for discovery.

As an interesting aside, TeV-scale extra dimensions may also manifest themselves in a dispersion in the propagation velocity of light in extragalactic space (17). Observations of the shortest flares, at the highest energies from the most distant objects can place tight constraints on theories with large extra dimensions. Such constraints have already been produced by TeV measurements (18) and could be dramatically improved with a future higher-sensitivity gamma-ray instrument, capable of detecting shorter flares from distant AGNs and GRBs. Thus, ground-based TeV gamma-ray astronomy probes TeV-scale particle physics both by providing a possible avenue for detection of a Kaluza-Klein particle and by constraining the the TeV^{-1}-scale structure of space-time from gamma-ray propagation effects.

A new class of theories (the so-called "little Higgs"

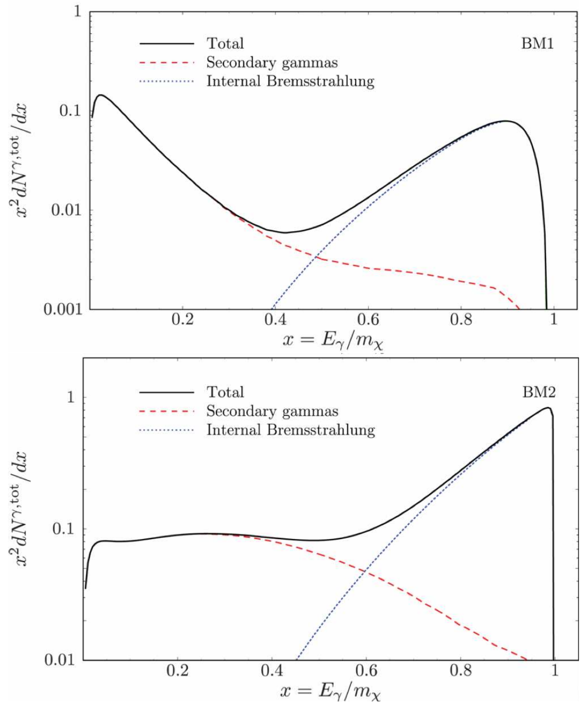

Fig. 2.—: Continuum emission from neutralino annihilation from mSUGRA models.

or LH models) has been proposed to extend the standard model to the TeV scale and offer an explanation for the lightness of the Higgs. The LH models predict a light (possibly composite) Higgs boson as well as other TeV-scale particles that could provide candidates for the dark matter in the $\sim$100 GeV or $\gtrsim$ 500 GeV mass range (19). However, only a small subset of the LH models have weak-scale masses and interactions together with a symmetry principle that protects the stability of the particle on a lifetime comparable to the age of the universe. In fact, for the composite Higgs, the particles (like their analog, the neutral pion) could decay with relatively short lifetimes. Still, this class of models (like other new physics at the TeV scale) could provide a viable dark matter candidate with an observable gamma-ray signature.

The recent discoveries of neutrino mass from measurements of atmospheric and solar neutrinos may also have a bearing on the prospects for gamma-ray detection of dark-matter. While the primordial density of light standard-model (SM) neutrinos ν_e, ν_μ and ν_τ will provide a very small hot-dark-matter contribution to the energy budget of the universe, they are ruled out as candidates for the CDM component needed to explain

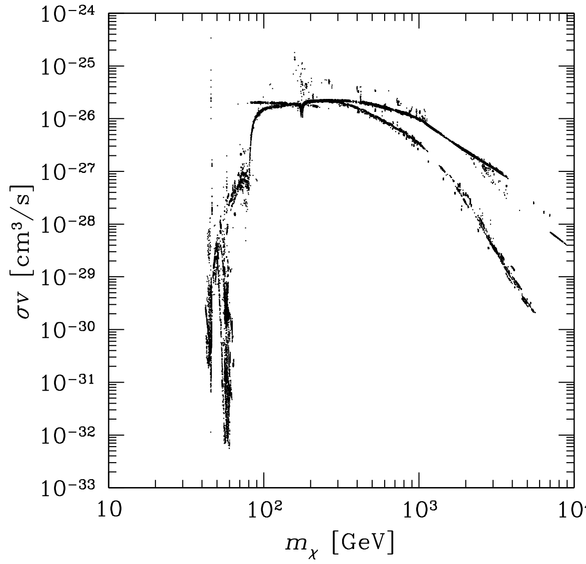

Fig. 3.—: Scatter plot of neutralino annihilation cross section versus neutralino mass for supersymmetric models that satisfy accelerator and WMAP constraints. A typical cross-section (assumed in our estimates) is $\sigma v \approx 2 \times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$.

structure formation. However, a new heavy neutrino (or the superpartner thereof) may provide a viable candidate for the CDM. Krauss, Nasri and Trodden (20) proposed that a right-handed neutrino with TeV mass could play a role in giving masses to otherwise massless standard model neutrinos through high-order loop corrections. This model is a version of the Zee model (21) that has been successfully applied to results on solar and atmospheric neutrino observations to explain the observed parameters of the mass and mixing matrix. A discrete Z_2 symmetry, and the fact that the right-handed Majorana neutrino N_R is typically lighter than the charged scalars in the theory, make the massive neutrino stable, and a natural dark matter candidate (22). Direct annihilation to a gamma-ray line $N_R N_R \to \gamma\gamma$ with a cross-section $\langle\sigma_{N_R N_R \to \gamma\gamma} v\rangle \approx 10^{-29}\mathrm{cm}^3\mathrm{s}^{-1}$ is at the limit of detectability and direct annihilation to charged leptons is also expected to give a very small cross-section. However, (22) have shown that internal bremsstrahlung can give rise to an observable gamma-ray continuum from decays to two leptons and a gamma-ray $N_R N_R \to l^+ l^- \gamma$. The three-body final state gives rise to a very hard spectrum that peaks near the N_R mass, then drops precipitously. Unlike direct annihilation to leptons, this non-helicity-suppressed process can have a large cross-section, with an annihilation rate a factor of α/π (where α is the fine structure constant) times the annihilation rate at freeze-out (with cross section $\langle\sigma v\rangle \approx 3 \times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$), and orders of magnitude lager than the helicity-suppressed two-body $N_R N_R \to l^+ + l^-$ rate typically considered in the past (22).

Recently, Bringmann, Bergström and Edsjö (23) have pointed out that internal-bremsstrahlung process could also play a role in neutralino annihilation, and in some cases result in a large enhancement in the continuum gamma-ray signal for certain model parameters. Fig. 1 shows the continuum emission from neutralino annihilation from mSUGRA models with particularly pronounced IB features, that could be observed in the gamma-ray spectrum. There are a number of different particle physics and astrophysical scenarios that can lead to the production of an observable gamma-ray signal with a spectral form that contains distinct features that can be connected, with high accuracy, to the underlying particle physics.

In what follows, we focus on predictions for the neutralino. While we show detailed results for the specific case of SUSY models and the neutralino, for any theory with a new weakly interacting thermal relic (e.g., the LKP) the model parameter space is tightly constrained by the observed relic abundance and hence the results for the overall gamma-ray signal level are fairly generic for any WIMP candidate. In the case of neutralino dark matter, the cross-sections for annihilation have been studied in detail by a number of groups. Fig. 3 shows the cross-section calculated for a range of parameters in supersymmetric parameter space as a function of mass. Only points that satisfy accelerator constraints and are compatible with a relic abundance matching the WMAP CMB measurements are shown. At high energies, the neutralino is either almost purely a Higgsino (for mSUGRA) or Wino (for anomaly-mediated SUSY breaking) resulting in the relatively narrow bands. Thus, the annihilation cross-section predictions for gamma-ray production from higher energy (~100 GeV–TeV) candidates are well constrained, with the particle-physics uncertainty contributing ~ one order of magnitude to the range of the predicted gamma-ray fluxes.

We elaborate further on the potential of γ-ray experiments to play a pivotal role in identifying the dark matter particle and in particular, how a next-generation γ-ray experiment can in fact provide information on the actual formation of structure in the Universe.

2. Dark Matter Annihilation into γ-rays, and the uncertainties in the predicted flux

For any of the scenarios that have been considered, the dark-matter particle must be neutral and does not couple directly to photons, however most annihilation channels ultimately lead to the production of photons through a number of indirect processes. While the total cross-section for gamma-ray production is constrained by the measured relic abundance of dark matter, the shape of the gamma-ray spectrum is sensitive to the details of the specific particle-physics scenario. Summarizing the previous discussion, dark matter annihilation may yield photons in three ways: (1) by the direct annihilation into a two-photon final state (or a $Z^0\gamma$ or $H\gamma$ final state) giving a nearly monoenergetic line, (2) through the annihilation into an intermediate state (e.g. a quark-antiquark pair), that subsequently decays and hadronizes, yielding photons through the decay of neutral pions and giving rise to a broad featureless continuum spectrum or (3) through internal-bremsstrahlung into a three-particle state, e.g. $\chi\chi \rightarrow W^+W^-\gamma$ yielding gamma-rays with a very hard spectrum and sharp cutoff. The cross section for the direct annihilation into two photons, or a photon and Z^0 are loop-suppressed and can be at least 2 orders of magnitude less than the processes that lead to the continuum emission. However, for some cases of interest (e.g., a massive Higgsino) the annihilation line can be substantially enhanced. Also, in the next-to-minimal supersymmetric standard model (NMSSM) with an extended Higgs sector, one-loop amplitudes for NMSSM neutralino pair annihilation to two photons and two gluons, extra diagrams with a light CP-odd Higgs boson exchange can strongly enhance the cross-section for the annihilation line. Such models have the added feature of providing a mechanism for electroweak baryogenesis (24). By combining Fermi measurements of the continuum, with higher energy constraints from ground-based ACT measurements, one can obtain constraints on the line to continuum ratio that could provide an important means of discriminating between different extensions to minimal supersymmetry or other dark matter scenarios

In general, the flux of γ-rays from a high-density annihilating region can be written as

$$\frac{dN_\gamma}{dAdt} = L\mathcal{P} \tag{1}$$

where,

$$L = \frac{1}{4\pi}\int_{\rm LOS} \rho^2(r)dl \tag{2}$$

contains the dependence to the distribution of dark matter, and

$$\mathcal{P} = \int_{E_{th}}^{M_\chi} \sum_i \frac{\langle\sigma v\rangle_i}{M_\chi^2}\frac{dN_{\gamma,i}}{dE}\,dE \tag{3}$$

is the particle physics function that contains the detailed physical properties of the dark matter particle. The sum over the index i represents the sum over the different photon production mechanisms. (In Eq. 2, M_χ is the neutralino mass, l is the line-of-sight distance while r is the radial distance from the center of the halo distribution. Note that this definition of L is similar to the definition of the J-factor used elsewhere in the literature (e.g., (30))

Given the fact that supersymmetry has not been detected yet, the uncertainty in the value of $\mathcal{P}$ is rather large. Sampling of the available supersymmetric parameter space reveals that the uncertainty in cross sections can be as large as 5 orders of magnitude if one covers the entire mass range down that extends over several orders of magnitude (see Fig. 3), but collapses considerably for $M_\chi \gtrsim$ 100 GeV. For supersymmetric dark matter, $\mathcal{P}$ can take a *maximum* value of approximately $\mathcal{P} \approx 10^{-28}\,\mathrm{cm^3 s^{-1} GeV^{-2}}$ when $M_\chi \approx 46\,\mathrm{GeV}$, $\sigma v = 5\times10^{-26}\,\mathrm{cm^3s^{-1}}$ and $E_{\rm th} = 5\,\mathrm{GeV}$ (with a more typical value of $\approx 2\times10^{-26}\,\mathrm{cm^3s^{-1}}$ at energies between 100 GeV and 1 TeV . On the other hand, for a threshold energy of $E_{\rm th} = 50\,\mathrm{GeV}$ and a particle mass of $M_\chi \approx 200\,\mathrm{GeV}$, the value is $\mathcal{P} \approx 10^{-31}\,\mathrm{cm^3s^{-1}GeV^{-2}}$.

It is important to emphasize that even though the actual value of $\mathcal{P}$ from supersymmetry can be orders of magnitude smaller, in theories with universal extra dimensions, both the cross section into a photon final state and the mass of the particle can actually be higher than this value.

The quantity L, on the other hand, contains all the information about the spatial distribution of dark matter. Specifically, L is proportional to the line of sight (LOS) integration of the square of the dark matter density. Dissipationless N-body simulations suggest the density profiles of dark matter halos can be described by the functional form

$$\rho(\tilde{r}) = \frac{\rho_s}{\tilde{r}^{\gamma}(1+\tilde{r})^{\delta-\gamma}} \tag{4}$$

where $\tilde{r} = r/r_s$ (e.g., (25; 26)).

The quantities ρ_s and r_s are the characteristic density and radius respectively, while γ sets the inner, and δ the outer slope of the distribution. Recent simulations suggest that $\delta \approx 3$, while the value of γ has a range of values, roughly $0.7 \leq \gamma \leq 1.2$ down to $\sim 0.1\%$ of the virial radius of the halo (27; 28). A change in the value of the inner slope γ between the values of 0.7 and 1.2 for a fixed halo mass results in a change in the value of L that is roughly 6 times smaller or higher respectively (29). The values of ρ_s and r_s for a dark matter halo of a given mass are obtained if one specifies the virial mass and concentration parameter. In general ρ_s (or the concentration parameter) depends solely on the redshift of collapse, while r_s depends on both the mass of the object as well as the redshift of collapse. In many previous studies the "fiducial" halo profile is that of Navaro, Frenck and White (NFW; (25)) derived from an empirical fit to the halo profile determined by N-body simulations and corresponding to Eq. 4 with $\delta = 3$ and $\gamma = 1$.

The main difficulty in estimating the value of L for a dark matter halo is due to the unknown density profiles in the regions from which the majority of the annihilation flux is emitted. Experimental data on the inner kiloparsec of our Galactic (or extragalactic) halos is sparse and theoretical understanding of these density profiles is limited by our lack of knowledge about the initial violent relaxation in dark matter halos, and the complicated physics behind the evolutionary compression of DM during the condensation of baryons in galactic cores. Both processes still lack a complete theoretical understanding. The uncertainty in the first is due to the unknown spectrum of density fluctuations at small spatial scales and difficulties of predicting their evolution in high resolution numerical simulations. The uncertainty in the second is due to the complexity of the gravitational interaction of the dark matter with the dissipative baryonic matter on small scales and in regions of high density. Experimentally, measurements of rotation curves and stellar velocity dispersion are limited by finite angular resolution and geometric projection effects. While progress is being made on both theoretical and experimental fronts, large uncertainties remain.

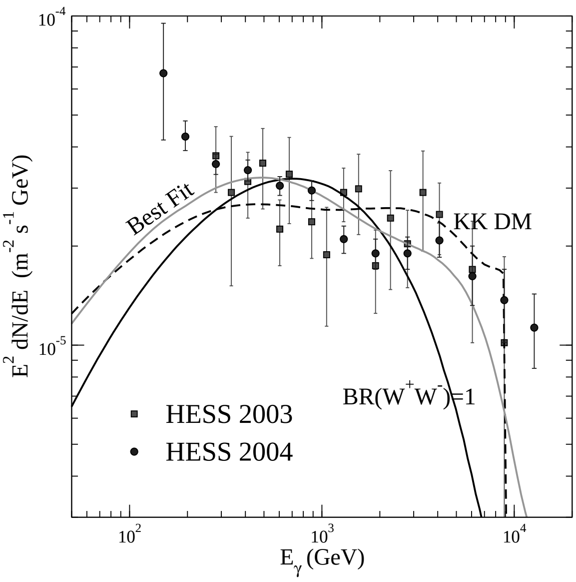

Fig. 4.—: The HESS 2003 (grey squares) and HESS 2004 (filled circles) data on the flux of GR from the GC, and the best fit to those data with a KK $B^{(1)}$ pair-annihilating lightest KK particle (dashed line), with a WIMP annihilating into a W^+W^- pair (black solid line), and with the best WIMP spectral function fit (light grey line).

3. Targets for Gamma-Ray Detection

The Galactic center has been considered the most promising target for the detection of dark matter annihilation, with a flux more than an order of magnitude larger than any potential galactic source (e.g., (30)). The detection of γ-rays from the region of Galactic Center by the Whipple and H.E.S.S. collaborations (31; 32) can, in principle, include a contribution from annihilating dark matter (33). While the flux and spectra of the Whipple and HESS detections are in agreement, the Cangaroo-II group reported the detection of high-energy gamma-ray emission from the GC region (97), with a considerably softer spectrum that now appears to be a transient effect (due to a variable source, or spurious detection) in view of the latest, detailed HESS results.

In Ref. (34) the possibility of interpreting the GR data from the GC in terms of WIMP pair annihilations was analyzed in full generality. Examples of fits to the HESS data with a Kaluza-Klein (KK) $B^{(1)}$ DM particle, with WIMPs annihilating into W^+W^- in 100% of the cases and with the best possible combination of final states, namely $\sim$ 30% into $b\bar{b}$ and $\sim$ 70% into $\tau^+\tau^-$ are shown in fig. 4. Those options give a χ^2 per degree of freedom of around 1.8, 2.7 and 1: only the best-fit

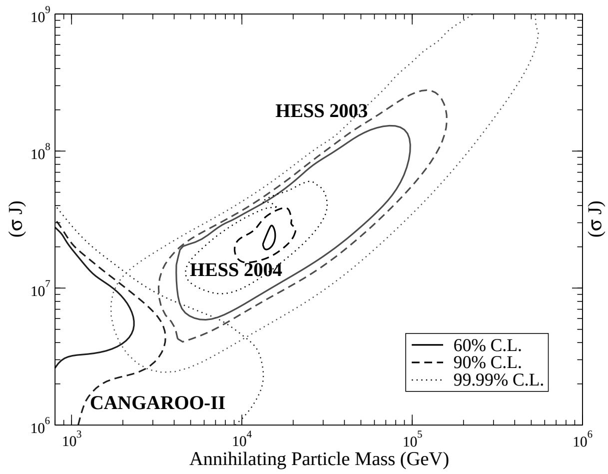

Fig. 5.—: Iso-confidence-level contours of "*best spectral functions*" fits to the Cangaroo-II and to the 2003 and 2004 HESS data, in the plane defined by the annihilating particle mass and by the quantity (σJ).

model is found to be statistically viable.

Using the Galactic-center data and assuming that the observed gamma-ray emission arises from dark-matter annihilation, Profumo (34) derived confidence intervals for the product of the total annihilation cross-section σ and the J-factor (characterizing the astrophysical uncertainty from the halo density profile) versus the neutralino mass m_χ. Iso-confidence-level contours in the $(m_\chi, (\sigma J))$ plane are shown in fig. 5. From the figure, it is clear that a dark-matter origin for the emission requires a DM mass range between 10-20 TeV. Further, a value of $(\sigma J) \approx 10^7$ implies either a very large astrophysical boost factor ($\approx 10^3$ larger than what expected for a NFW DM profile), or a similar enhancement in the CDM relic abundance compared with the expectations for thermal freeze-out

Ref. (34) showed that some supersymmetric models can accommodate large enough pair annihilation cross sections and masses to both give a good fit to the HESS data and thermally produce the right DM abundance even though, from a particle physics point of view, these are not the most natural models. An example is a minimal anomaly-mediated SUSY breaking scenario with non-universal Higgs masses. For some choices of model parameters, such a dark matter particle could even be directly detected at ton-sized direct detection experiments, even though the lightest neutralino mass is in the several TeV range (34).

However, the interpretation is particularly complicated since the center of our own Milky Way galaxy has a relatively low mass-to-light ratio and is dominated by matter in the form of a central massive black hole and a number of other young massive stars, supernova remnants and compact stellar remnants. Moreover, the lack of any feature in the power-law spectrum measured b HESS, and the extent of this spectrum up to energies above 10 TeV makes a dark-matter interpretation difficult.

A way of dealing with this background is to exclude the galactic center source seen by HESS, and instead look at an annulus about the Galactic center position (35; 36). Even though the background grows in proportion to the solid angle of the annular region (and the sensitivity degrades as the square-root of this solid angle) for a sufficiently shallow halo profile, the signal-to-noise ratio for detection continues to grow out to large angles. Moreover, any component of diffuse contaminating background falls off more steeply as a function of latitude than the annihilation of the smooth component of the dark matter halo. This result may even be enhanced by the presence of other bound high density structures within the inner parts of the Milky Way (37).

We make a conservative estimate of the signal from an annulus centered on the galactic center. For this calculation, we assume that the Milky Way halo has a profile as given by Navaro, Frenck and White (25) (NFW profile) with a scale radius of $r_s = 21.7$ kpc and a central density of $\rho_s = 5.38\, M_\odot\, \mathrm{kpc}^{-3}$ from Fornengo et al. (38). To be somewhat more conservative, in light of more recent N-body simulations that show a flattening of the inner halo profile, we assume a 10 pc constant density core. The minimum angle for the annular region is set by the assumed PSF for a future instrument. We assume that the flux from the point source at the GC (or from the diluted contribution from the galactic ridge emission) will fall below 10% of the GC value, 0.2 deg from the position of Sgr A*. The optimum angular radius for the outer bound on the annulus is 12 deg (see (36) for details), somewhat beyond the largest field of view envisioned for a future imaging ACT (with a more realistic value of 6-8 deg). As shown in Fig. 6, Fermi might also have adequate sensitivity and angular resolution to detect the continuum emission and separate this from the other point sources. If the neutralino mass is large enough (above several TeV) and one chooses favorable parameters for the annihilation cross-section and density, EAS detectors have the

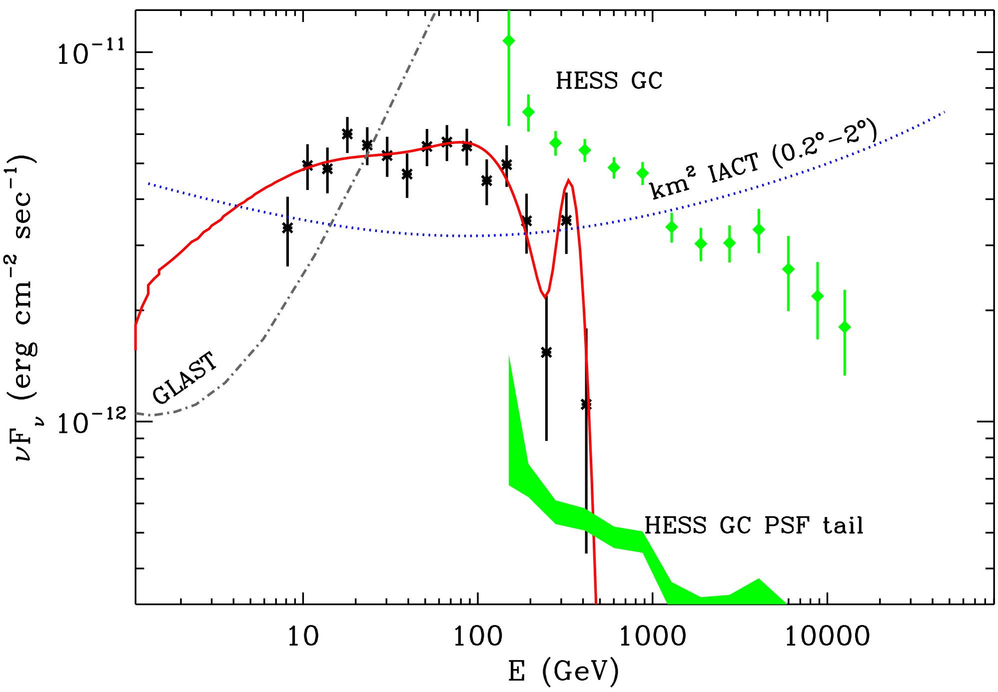

Fig. 6.—: Gamma-ray spectrum from dark matter annihilation in an annulus between 0.2° and 2° about the Galactic center assuming an NFW halo with a central density of $\rho_s = 5.4 \times 10^6\, M_\odot/\mathrm{kpc}^3$ and a scale radius of $r_s = 21.7\,\mathrm{kpc}$. We show the HESS spectrum of the point source near the GC, and 10% of this value assumed to bleed into the annulus from the tails of the gamma-ray point-spread-function. Here we assume a 200 hour exposure of a a km^2 IACT instrument. The reduced sensitivity, compared with that for a point source, comes from integrating the hadronic, electron, and diffuse gamma-ray background over the relatively large solid angle of the annulus.

large field-of-view required to observe such extended sources as well as other regions of emission along the galactic plane. However, these detectors lack the good angular and energy resolution to separate this emission from other point sources and would require follow-up observations by more sensitive instruments such as imaging ACT arrays. For the IACT sensitivity, we assume that we have an instrument with effective area of 1 km^2, an exposure of 200 hrs, and that the background comes from cosmic-ray electrons, cosmic-ray atmospheric showers, and diffuse gamma-rays following the method given in Ref. (30). For the diffuse gamma-ray spectrum, we take the EGRET diffuse flux, and assume that it continues with a relatively hard $\sim E^{-2.5}$ spectrum up to TeV energies. We also assume that the largest practical angular radius of the annular region is 2 deg, a reasonable value for a moderately wide-field-of view future instrument. The simulated spectrum is calculated for a typical annihilation cross section of $\langle\sigma v\rangle = 2 \times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$ and for an arbitrary set of branching ratios corresponding to 50% $\tau\bar{\tau}$, 50% $b\bar{b}$ and a line-to-continuum ratio of 6×10^{-3}. Assuming a 15% energy resolution, we obtain the simulated spectrum shown in Fig. 6. This demonstrates that a future instrument could observe a spectral signature of dark matter annihilation in the region around the GC, above the residual astrophysical backgrounds. To search for gamma-ray emission from dark-matter annihilation in the Galactic center region, the requirements for the future instrument include: a large effective area ($\sim$1 km^2), a moderately large field of view ($\gtrsim 7°$ diameter), a good energy resolution ($\lesssim 15\%$), a low energy threshold ($\lesssim 50$ GeV), excellent angular resolution to exclude contributions from astrophysical point-sources ($<\sim 0.1°$) and a location at low geographic latitude (preferably in the southern hemisphere) for small-zenith-angle low-threshold measurements of the GC region.

However, given the large backgrounds in our own galaxy, the observation of a wider class of astrophysical targets is desirable. A future km^2 ACT array should, for the first time, have the sensitivity required to detect extragalactic sources such as Dwarf galaxies, without resorting to very optimistic assumptions about the halo distribution. The VERITAS collaboration previously undertook such an observing program with the Whipple 10m telescope and reported upper limits for several extragalactic targets (M33, Ursa Minor & Draco dwarf galaxies, M15) (39; 40; 41). The HESS group published limits on the Sagittarius dwarf galaxy and the resulting constraints on the halo models (42). However, more sensitivity is required to detect a more generic annihilation flux from such sources.

3.1. Dwarf Spheroidals

Dwarf spheroidal (dSph) systems are ideal dark matter laboratories because astrophysical backgrounds and baryon-dark matter interactions are expected not to play a major role in the distribution of dark matter. Furthermore, the mass–to–light ratio in dSphs can be very large, up to a few hundred, showing that they are largely dark-matter dominated systems. Numerous theoretical studies point to the potential for detecting dark matter annihilation in dwarf spheroidal galaxies or galaxies in the local group based on rough assumptions of the distribution of dark matter (34; 43; 44; 46; 47). However, with the advent of more data on the stellar content of dSphs, it has recently been possible to perform a likelihood analysis on the potential dark matter profiles that these systems could posses. Under the assumption that dSphs are in equilibrium, the radial component of the stellar velocity dispersion is linked to the gravitational potential of the system through the Jeans equation. This approach (utilized in (45; 29; 48)) has the significant advantage that observational data dictate the distribution of dark matter with a minimum number of theoretical assumptions. The main results of these studies are that dSphs are very good systems for the search for dark matter annihilation, because most of the uncertainties in the distribution of dark matter can be well quantified and understood. In addition, dSphs are expected to be relatively free of intrinsic γ-ray emission from other astrophysical sources, thus eliminating contaminating background that may hinder the interpretation of any observation. Assuming a scenario for supersymmetric dark matter where $M_\chi = 200\,\mathrm{GeV}$, $E_{\mathrm{th}} = 50\,\mathrm{GeV}$ and $\mathcal{P} \approx 10^{-31}\,\mathrm{cm}^3\mathrm{s}^{-1}\mathrm{GeV}^{-2}$, the maximum expected fluxes from 9 dSphs studied in (29; 48) can be as large as 10^{-12} photons cm^{-2} s^{-1} (for Willman 1). Observing γ-rays from dark matter annihilation in dwarf spheroidals is of fundamental importance for 2 reasons: First and foremost, these observations can lead to an identification of the dark matter, especially if line emission or other distinct features in the continuum are detected and second, they will provide information on the actual spatial distribution of dark matter halos in these important objects. If there is a weakly interacting thermal relic, then γ-ray telescopes can tell us something about non-linear structure formation, a task unattainable by any other experimental methods.

Fig. 7 shows an example of one possible spectrum that might be measured for Ursa Minor given conservative assumptions including: a typical annihilation cross-section, a halo distribution constrained by stellar velocity measurements (from Strigari et al. (48)) and a modest boost factor of $b = 3$ at the low end of the expected range for such halos. This prediction demonstrates that detection from Dwarf galaxies is most likely out of reach of the current generation of IACT experiments (HESS and VERITAS) or proposed EAS experiments, but may be within reach of a future km^{2}IACT instrument, if the point-source sensitivity is improved by an order of magnitude, the energy resolution is good enough to resolve the spectral features (better than 15%) and the energy threshold can be pushed well below 100 GeV.

With the advent of the Sloan Digital Sky Survey (SDSS), the number of known dSph satellites of the local group has roughly doubled during the last decade (49). Since the survey is concentrated around the north Galactic pole, it is quite likely that there are many more dSph satellites waiting to be discovered. For an isotropic distribution, and assuming that SDDS has found all the satellites in its field of view, we would expect ~ 50 dwarfs in all. Since simulation data suggests that dwarf satellites lie preferentially along the major axis of the host galaxy, the number of Milky-Way dwarf satellites could be well above this estimate. With more dwarf galaxies, and increasingly detailed studies of stellar velocities in these objects, this class of sources holds great promise for constraints on dark matter halos and indirect detection of dark matter. Since many of these discoveries are very new, detailed astronomical measurements are still required to resolve the role of dark matter in individual sources. For example, for the

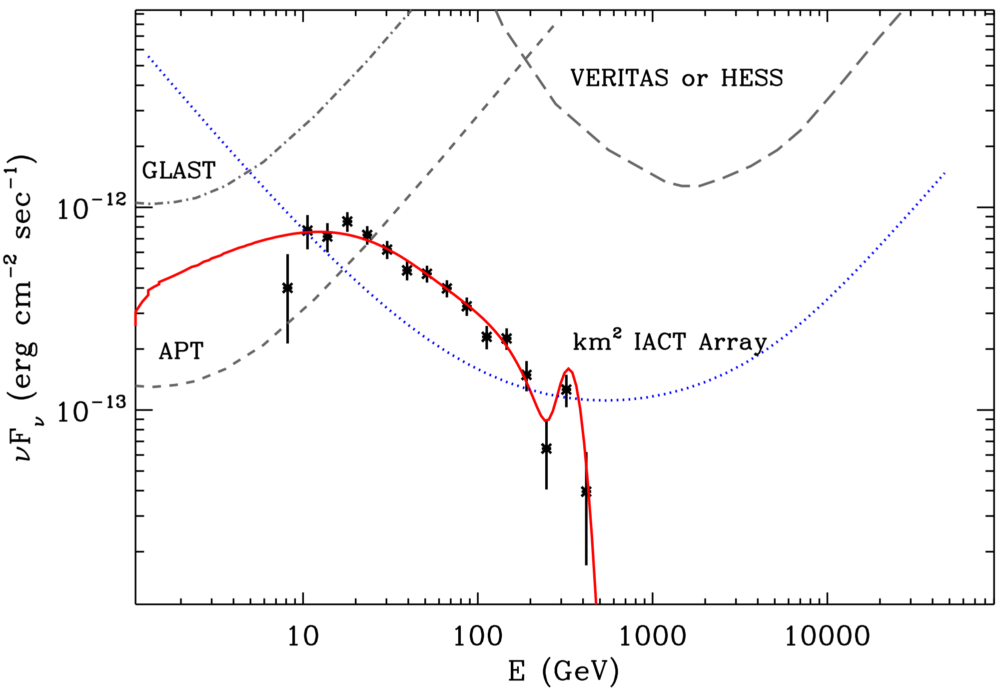

Fig. 7.—: Predicted gamma-ray signal from the dwarf spheroidal galaxy Ursa Minor for neutralino mass of 330 GeV, branching into $\tau^+\tau-$ 20% of the time, and into $b\bar{b}$ 80% of the time and with a line to continuum ratio of $2{\times}10^{-3}$. We assume a typical annihilation cross-section of $2 \times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$ the halo values from Strigari et al. (48) with $r_s = 0.86\,\mathrm{kpc}$ and central density $\rho_s = 7.9 \times 10^7\, M_\odot/\mathrm{kpc}^3$. We also assume a modest boost factor of $b = 3$ from halo substructure. We assume an ideal instrument with an effective area of 1 km^2 and sensitivity limited only by the electron background, diffuse gamma-ray background (assuming an $\sim E^{-2.5}$ spectrum connecting to the EGRET points) and cosmic-ray background (10 times lower than current instruments). For this idealized IACT array, we do not include the effect of a threshold due to night-sky-background, and assume an energy resolution of 15%. The data points are simulated given the signal-to-noise expected for the theoretical model compared with our anticipated instrument sensitivity.

new object Willman I, some have argued that this is a globular cluster while others have made the case that despite it's relatively small mass, this is a dark-matter dominated object and not a globular cluster (50). Other studies challenge the inferences about the dark matter dominance in dSphs attributing the rise in rotation velocities in the outer parts of dSphs to tidal effects rather than the gravitational potential (51). Future progress in this blossoming area of astronomy could provide important additional guidance for a more focused survey on the most promising sources using pointed observations with very deep exposures.

3.2. Local group galaxies

Local group galaxies offer attractive targets for the search of γ-rays form dark matter annihilation for many of the same reasons dSph galaxies do: they are relatively small systems, with relatively high mass-to-light ratios (except M31). Relative to dSphs, the influence of baryons in the central regions is higher, especially if a black hole is present (such as M32). Nevertheless, their relative proximity and size make them viable targets that should be explored. Recently, Wood et al. (2007) (41) used the Whipple 10m telescope and placed bounds on the annihilation cross section of neutralinos assuming a distribution of dark matter in the halos of M32 and M33 that resembles dark matter halos seen in N-body simulations. While these observations with Whipple and now with VERITAS and HESS provide interesting limits on some of the more extreme astrophysical or particle physics scenario, more sensitive observations are needed if one makes more conservative estimates. Even with an order of magnitude increase in sensitivity over the current generation experiments, it is still possible that Dwarf or local-group galaxies will evade detection with the next generation

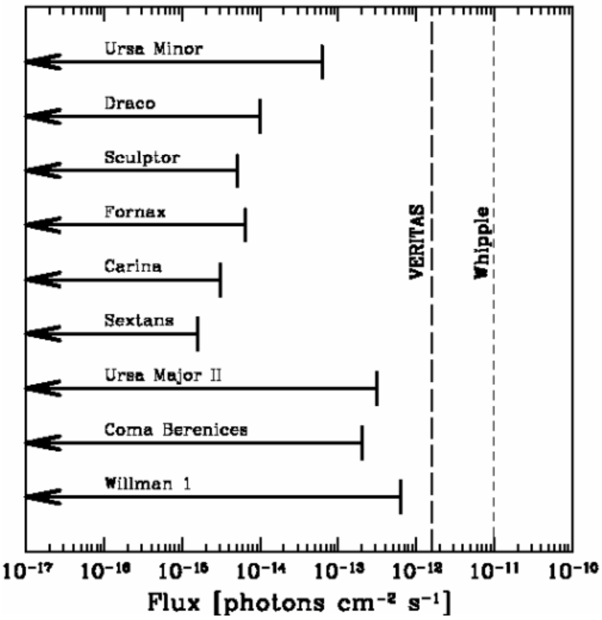

Fig. 8.—: Prospects for detecting the most prominent Dwarf-galaxy targets for dark matter annihilation. Upper-limit bars show the range of theoretical predictions (98) with fluxes dropping below the level of detectability as one traverses the full range of parameter space including the neutralino mass, cross-section and halo distribution. The plot includes dark-matter dominated dwarf spheroidal systems in the Milky Way halo, including promising sources located at high galactic latitude and with virtually no known intrinsic γ ray emission from astrophysical sources. The thin-dashed line represents the sensitivity of Whipple, while the long-dashed line depicts the sensitivity of VERITAS.

detector without some enhancement in the central halo (e.g. a cusp steepened by the stellar population or a large boost factor). Given this uncertainty the best strategy for detecting dark matter from Dwarf galaxies, or local group galaxies is to observe an ensemble of sources, taking advantage of the source-to-source variance in the halo profile until better constraints are available from new astronomical measurements (e.g., stellar velocity dispersion or rotation curves).

3.3. Detecting the Milky Way Substructure

A generic prediction of the hierarchical structure formation scenario in cold dark matter (CDM) cosmologies is the presence of rich substructure; bound dark matter halos within larger, host halos. Small dark matter halos form earlier, and therefore have higher characteristic densities. This makes some of these subhalos able to withstand tidal disruption as they sink in the potential well of their host halo due to dynamical friction. Unfortunately, even though this is a natural outcome of CDM, there is no clear explanation as to why the Milky Way appears to contain a factor of 10-100 *fewer* subhalos than it should, based on CDM predictions (53; 54). Several solutions to this problem have been suggested, such as changing the properties of the dark matter particle (e.g., (55; 56; 57)), modifying the spectrum of density fluctuations that seed structure growth (e.g., (58; 59)), or invoking astrophysical feedback processes that prevent baryonic infall and cooling (e.g., (60; 61; 62)). The most direct experimental way to probe the presence of otherwise dark substructure in the Milky Way is through γ-ray observations. Theoretical studies (63), as well as numerical simulations of a Milky Way-size halo (37), predict that given the probability of an otherwise completely dark subhalo nearby, the expected flux in γ-rays can be as large as $\sim 10^{-13}$ cm^{-2} s^{-1}.

3.4. Detecting Microhalos

The *smallest* dark matter halos formed are set by the RMS dark matter particle velocities at kinetic decoupling, the energy scale at which momentum–changing interactions cease to be effective (64; 65; 66; 67; 68; 69; 70; 71). For supersymmetric dark matter this cutoff scale fives a mass range for *microhalos* of around $10^{-13} \leq [M/M_{\odot}] \leq 10^{-2}$, depending on the value of the kinetic decoupling temperature which is set by the supersymmetric parameters. While the survival of microhalos in the Solar neighborhood is still under debate, there are indications that some fraction ($\sim 20\%$) may still be present. In this case, microhalos could even be detected via the proper motion of their γ-ray signal (72; 73). Microhalos that exhibit proper motion must be close enough that their proper motion is above a detection threshold set by the angular resolution and length of time over which the source can be monitored(given by the lifetime of the observatory). Microhalos must be abundant enough so that at least one is within the volume set by this proper motion requirement. The expected flux from a microhalo that may exhibit detectable proper motion (73) is $\sim 10^{-15}$ cm^{-2} s^{-1}. Such objects are most likely to be detected by very wide-field instruments like Fermi. Follow-up measurements with IACT arrays would be required to determine the characteristics of the spectrum and angular extent of these sources at higher energies.

3.5. Spikes around Supermassive and Intermediate-Mass Black Holes

There are other potential dark matter sources in our own Galaxy that may be formed by a gravitational interplay of dark halos and baryonic matter. In particular, it is possible that a number of intermediate-mass black holes (IMBHs) with cuspy halos, might exist in our own galaxy. The effect of the formation of a central object on the surrounding distribution of matter has been investigated in Refs. (74; 75; 76; 77) and for the first time in the framework of DM annihilations in Ref. (78). It was shown that the *adiabatic* growth of a massive object at the center of a power-law distribution of DM, with index γ, induces a redistribution of matter into a new power-law (dubbed "spike") with index

$$\gamma_{sp} = (9 - 2\gamma)/(4 - \gamma) \quad . \tag{5}$$

This formula is valid over a region of size $R_{sp} \approx 0.2\, r_{BH}$, where r_{BH} is the radius of gravitational influence of the black hole, defined implicitly as $M(< r_{BH}) = M_{BH}$, where $M(< r)$ denotes the mass of the DM distribution within a sphere of radius r, and where M_{BH} is the mass of the Black Hole (79). The process of adiabatic growth is, in particular, valid for the SMBH at the galactic center. A critical assessment of the formation *and survival* of the central spike, over cosmological timescales, is presented in Refs. (80; 81) and references therein. Adiabatic spikes are rather fragile structures, that require fine-tuned conditions to form at the center of galactic halos (82), and that can be easily destroyed by dynamical processes such as major mergers (83) and gravitational scattering off stars (84; 80).

However Intermediate Mass BHs, with mass $10^2 < M/\mathrm{M}_\odot < 10^6$, are not affected by these destructive processes. Scenarios that seek to explain the observed population and evolutionary history of supermassive-black-holes actually result in the prediction of a large population of wandering IMBHs, with a number in our own Galaxy. They may form in rare, overdense regions at high redshift, $z \sim 20$, as remnants of Population III stars, and have a characteristic mass-scale of a few $10^2\,\mathrm{M}_\odot$ (85; 86; 87; 88; 89). Alternatively, IMBHs may form directly out of cold gas in early-forming halos and are typified by a larger mass scale of order $10^5\,\mathrm{M}_\odot$ (90). We show in Fig. 3.5 the number of objects that can be detected as a function of the detector sensitivity. The spiky halos around galactic intermediate-mass black holes

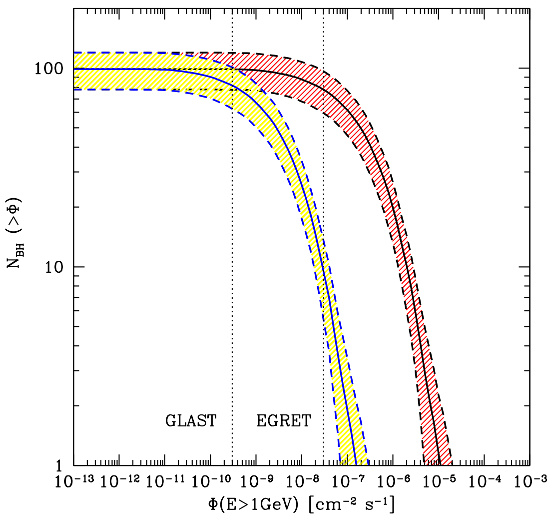

Fig. 9.—: IMBHs integrated luminosity function, i.e. number of IMBHs that can be detected from experiments with point source sensitivity Φ (above 1 GeV), as a function of Φ. We show for comparison the 5σ point source sensitivity above 1 GeV of EGRET and Fermi (GLAST) in 1 year. From Ref. (86).

could provide a large enhancement in the gamma-ray signal that could be effectively detected by all-sky low-threshold instruments such as Fermi then followed-up by ground-based measurements. Over most of the allowed parameter space, Fermi would detect the onset of the continuum spectrum but would lack the sensitivity to measure the detailed spectral shape above hundreds of GeV. Ground-based measurements with good point-source sensitivity, and good energy resolution (10-15%) would be necessary to follow-up these detections to measure the spectral cutoff and other features of the annihilation spectrum needed to clearly identify a dark-matter origin for the gamma-ray signal.

High energy gamma-ray astronomy can also indirectly provide information about the formation history of IMBHs through a very different avenue, i.e., infrared absorption measurements of gamma-rays from distant AGN. For example, the early population-III stars that may seed the growth of IMBHs are likely to be massive (100 $M_\odot$) stars that form in dark matter clumps of mass $\sim 10^6 M_\odot$. These short lived stars would result in a large contribution to the total amount of visible and UV light in the early (large-redshift) universe, that contribute to the present-day diffuse infrared background. Present observations by Whipple, HEGRA, MAGIC and HESS already provide constraints on the contribution from population-III stars. Gamma-ray astronomy has the unique potential to provide important constraints on the history of structure formation in the universe through observations of the annihilation signal from dark-matter halos on a range of mass scales (including IMBH halos) in addition to probing the history of star formation through measurements of the diffuse infrared background radiation.

3.6. Globular clusters

Globular clusters are relatively low mass-to-light ratio bound systems in the Milky Way that are dominated by a dense stellar core. The presence of dark matter in the core of a collapsed globular cluster is questionable because it is expected that 2-body stellar interactions will deplete dark matter from the region. On the other hand, if there is any dark matter left-over from the core-collapse relaxation process, it is possible that the dense stellar core would adiabatically steepen the distribution of dark matter, thus making some dense globular clusters potential targets for dark matter detection. Wood et al. (2007) (41) observed the relatively close M15 globular cluster with the Whipple 10m telescope, and placed upper bounds on the cross section for dark matter annihilation.

4. Complementarity of γ-Ray Searches with Other Methods for Dark Matter Searches

Both Fermi and the LHC are expected to become operational in 2008. What guidance will these instruments provide for a future ground-based experiment? The ATLAS and CMS experiments at the Large Hadron Collider (LHC) are designed to directly discover new supersymmetric particles in the range of a few $\sim$ 100 GeV/c^2 and will start collecting data in the very near future. The LHC alone will not, under even the most optimistic circumstances, provide all of the answers about the nature of dark matter. In general, a combination of laboratory (LHC, ILC) detection and astrophysical observations or direct detection experiments will be required to pin down all of the supersymmetric parameters and to make the complete case that a new particle observed in the laboratory really constitutes the dark matter. Due to the fact that the continuum gamma-ray signal depends directly on the total annihilation cross-section, there are relatively tight constraints on the gamma-ray production cross-section from the cosmological constraints on the relic abundance. For direct detection, on the other hand, the nuclear recoil cross-section is only indirectly related to the total annihilation cross-section and thus there are a number of perfectly viable model parameters that fall many orders of magnitude below any direct detection experiment that may be built in the foreseeable future. Thus gamma-ray astronomy is unique in that the detection cross-section is closely related to the total annihilation cross section that determines the relic abundance. A given theoretical scenario of SUSY breaking at low energies, e.g. mSUGRA, SplitSUSY, non-universal SUGRA, MSSM-25, AMSB, etc., reduces the available parameter phase space. Therefore, it is natural to expect that, for some set of the parameters, the neutralino might be detected by all experimental techniques, while in other cases only a single method has sufficient sensitivity to make a detection (91). Only a combination of accelerator, direct, and indirect searches would cover the supersymmetric parameter space (92). For example, the mass range of neutralinos in the MSSM is currently constrained by accelerator searches to be above a few GeV (93; 94) and by the unitarity limit on the thermal relic to be below $\sim$ 100 TeV (95) (a narrower region would result if specific theoretical assumptions are made, e.g. mSUGRA).

For the LHC to see the lightest stable SUSY particle, it must first produce a gluino from which the neutralino is produced. This limits the reach of the LHC up to neutralino masses of $m_\chi \approx$ 300GeV, well below the upper end of the allowed mass range. Direct detection of WIMP-nucleon recoil is most sensitive in the 60 to 600 GeV regime. Indirect observations of self-annihilating neutralinos through $\gamma-$rays with energies lower than $\sim$ 100 GeV will best be accomplished by Fermi, while VERITAS and the other ground-based $\gamma-$ ray observatories will play critical role in searches for neutralinos with mass larger than $\sim$ 100 GeV.

While direct detection and accelerator searches have an exciting discovery potential, it should be emphasized that there is a large region of parameter space for which gamma-ray instruments could provide the only detection for cases where the nuclear recoil cross-section falls below the threshold of any planned direct detection experiment, or the mass is out of range of the LHC or even the ILC. Any comprehensive scientific roadmap that puts the discovery of dark matter as its priority must include support for a future, high-sensitivity ground-based gamma-ray experiment in addition to accelerator and direct searches

But the next 5-10 years of DM research may provide us with a large amount of experimental results coming from LHC, direct DM searches (8; 10; 9; 11; 12; 14) and indirect observations of astrophysical γ-rays. Current gamma-ray experiments such as AGILE, Fermi, VERITAS, HESS and MAGIC will continue making observations of astrophysical sources that may support very high density dark matter spikes and may, with luck, provide a first detection of dark matter. The wide field-of-view Fermi instrument could provide serendipitous detections of otherwise dark, dark matter halos, and search for the unique dark matter annihilation signal in the isotropic cosmological background. EAS experiments will provide evidence about the diffuse galactic background at the highest energies, helping to understand backgrounds for dark matter searches and even offering the potential for discovery of some unforeseen very high mass, nonthermal relic that form the dark matter. All of these results will guide the dark matter research which can be conducted by a future ground-based observatory needed to study the dark matter halos, and would affect strongly the design parameters of such an observatory.

To briefly summarize the interplay between the LHC, Fermi and a future ground-based gamma-ray instrument, it is necessary to consider several different regimes for the mass of a putative dark matter particle:

- *Case I:* If $m_\chi \sim 100\,\mathrm{GeV}$ and the LHC sees the LSP, Fermi will probably provide the most sensitive measurements of the continuum radiation and will be needed to demonstrate that a supersymmetric particle constitutes the dark matter (98). Ground-based measurements will be needed to constrain the line-to-continuum ratio to better determine the supersymmetric parameters or to obtain adequate photon statistics (limited by the $\sim\mathrm{m}^2$ effective area of Fermi) to obtain the smoking gun signature of annihilation by observing line emission.

- *Case II:* If $100\,\mathrm{GeV} < m_\chi < 300\,\mathrm{GeV}$, the LHC could still see the neutralino, but both the line and continuum emission could be better detected with a a low-threshold (i.e., 20-40 GeV threshold) ground-based experiment than with Fermi, if the source location is known. Again these gamma-ray measurements are still required to demonstrate that a supersymmetric particle constitutes astrophysical halos, and to further measure supersymmetric parameters (3).

- *Case III:* If $m_\chi > 300\,\mathrm{GeV}$ future direct-detection experiments and ground-based gamma-ray experiments may be able to detect the neutralinos. Only ground-based instruments will be able to determine the halo parameters, and will provide additional constraints on SUSY parameter space somewhat orthogonal to the constraints provided by the determination of the direct detection cross-sections. For a sizeable fraction of parameter space, nuclear recoil cross-sections may be too small for direct detection but the total annihilation cross section could still be large enough for a gamma-ray detection. Detection at very high energies would be particularly important for non-SUSY dark matter candidates such as the lightest Kaluza-Klein partner, where current constraints put the likely mass range above the TeV scale. Since TeV-scale neutralinos are likely to be either pure Higgsino or pure Wino particles, particle-physics uncertainties are expected to be smaller in this VHE energy regime.

5. Conclusions

A next-generation γ-ray telescope has the unique ability to make the connection from particles detected in the laboratory to the dark matter that dominates the density of matter in the universe, and to provide important constraints that help to identify the nature of the dark matter particle. The main findings of our study about the potential impact of gamma-ray measurements on the dark-matter problem and the requirements for a future instrument are summarized below:

- Compared with all other detection techniques (direct and indirect), γ-ray measurements of dark-matter are unique in going beyond a detection of the local halo to providing a measurement of the actual distribution of dark matter on the sky. Such measurements are needed to understand the nature of the dominant gravitational component of our own Galaxy, and the role of dark matter in the formation of structure in the Universe.

- There are a number of different particle physics and astrophysical scenarios that can lead to the production of a gamma-ray signal with large variations in the total flux and spectral shape. The spectral form of the gamma-ray emission will be universal, and contains distinct features that can be connected, with high accuracy, to the underlying particle physics.

- The annihilation cross-section for gamma-ray production from higher energy (TeV) candidates are well constrained by measurements of the relic abundance of dark matter, with the particle-physics uncertainty contributing $\sim$ one order of magnitude to the range of the predicted gamma-ray fluxes.

- The Galactic center is predicted to be the strongest source of gamma-rays from dark matter annihilation but contains large astrophysical backgrounds. To search for gamma-ray emission from dark-matter annihilation in the Galactic center region, the requirements for the future instrument include: extremely good angular resolution to reject background from other point sources, a moderately large field of view ($\gtrsim 7^\circ$ diameter), a good energy resolution ($\lesssim 15\%$), a low energy threshold $\lesssim 50$ GeV, and location at a southern hemisphere site.

- Observations of local-group dwarf galaxies may provide the cleanest laboratory for dark-matter searches, since these dark-matter dominated objects are expected to lack other astrophysical backgrounds. For these observations, a very large effective area and excellent point-source sensitivity down to $\lesssim 50$ GeV is required. Energy resolution better than 15-20% is required to determine the spectral shape. Currently, the best strategy for detecting dark matter from dwarf galaxies, globular clusters or local group galaxies is to observe an ensemble of sources, taking advantage of the source-to-source variance in the halo profile that may lead to large enhancements in the signal from some sources, although improvements in constraints on the dark-matter density profile from future detailed astronomical measurements (e.g., from stellar velocity dispersion) will allow for a refinement of the list of most promising targets.

- Observations of halo-substructure could provide important new constraints on CDM structure formation, providing information on the mass of the first building blocks of structure, and on the kinetic decoupling temperature. The most direct experimental way to probe the presence of otherwise dark halo substructure in the Milky Way is through γ-ray observations. Space-based low-threshold all-sky measurements will be most effective for identifying candidate objects, but ground-based measurements will be required to determine the detailed spectral shape (cutoff, line-to-continuum ratio) needed to identify the dark matter candidate.

- The spiky halos around galactic intermediate-mass black holes could provide a large enhancement in the gamma-ray signal that could be effectively detected by all-sky low-threshold instruments such as Fermi or a future space-based instrument, then followed-up by ground-based measurements. Over most of the allowed parameter space, Fermi would detect the onset of the continuum spectrum but would lack the sensitivity to measure the detailed spectral shape above hundreds of GeV. Ground-based measurements with good point-source sensitivity, and good energy resolution (10-15%) would be necessary to follow-up these detections to measure the spectral cutoff and other features of the annihilation spectrum needed to clearly identify a dark-matter origin of the gamma-ray signal.

- While a space-based instrument or future IACT arrays are probably the only means of providing the large effective area, low threshold, energy and angular resolution for detailed measurements of gamma-rays from dark matter annihilation, future EAS experiments like HAWC can also play a useful role. Future EAS experiments, with their wide field of view and long exposure time, also have the potential for serendipitous discovery of some corners of parameter space, in particular for nonthermal relics and mass close to the unitarity limit. The good sensitivity of EAS experiments can provide important measurements of diffuse, hard-spectra galactic backgrounds.

- Gamma-ray astronomy has the unique potential to provide important constraints on the history of structure formation in the universe through dark-matter observations of dark-matter halos on a range of mass scales (including IMBH halos) in addition to probing the history of star formation through measurements of the diffuse infrared background radiation.

- In general, a combination of laboratory (LHC, ILC) detection and astrophysical observations or direct detection experiments will be required to pin down all of the supersymmetric parameters and to make the complete case that a new particle observed in the laboratory really constitutes the dark matter.

- Gamma-ray astronomy is unique in that the detection cross-section is closely related to the total annihilation cross section that determines the relic abundance.

  In closing, we reiterate that a comprehensive plan for uncovering the nature of dark matter must include gamma-ray measurements. With an order of magnitude improvement in sensitivity and reduction in energy threshold, a future IACT array should have adequate sensitivity to probe much of the most generic parameter space for a number of sources including Galactic substructure, Dwarf galaxies and other extragalactic objects.

REFERENCES

Spergel, D.N., *et al.* [WMAP Collaboration], Astrophys. J. Suppl. **170**, 377 (2007).

Percival, W.J., et al., Astrophys. J. **657**, 645 (2007)

Baltz, E.A., P5 presentation (2006)

Zwicky, F., Helvetica Physica Acta **6**, 110–127 (1933).

Cowsik, R., McClelland, J., ApJ, **180**, 7 (1973).

Clowe, D., et al., ApJ, **648**, (2006) L109.

Baltz, E.A., et al., Phys. Rev. D., **74**, 103521 (2006)

Aprile, E., et al., New Astron. Rev., **49**, 289 (2005)

Klapdor-Kleingrothaus, H.V., Krivosheina, I.V., Nucl. Phys. B. (Proc. Suppl.), **145**, 237 (2005).

Klapdor-Kleingrothaus, H.V., et al., Nucl. Inst. and Methods Phys. Res. A, **481**, 149 (2002).

Bisset, R., et al., Nucl. Phys. B. (Proc. Suppl.), **173**, 164 (2007).

Akerib, D.S., et al., Nucl. Inst. and Methods Phys. Res. A, **559**, 411 (2005).

Morales, A., TAUP99, Paris (1999).

Sanglard, V., et al., Nucl. Phys. B. (Proc. Suppl.), **173**, 99.

Ibarra, A., Tran, D., Phys. Rev. Lett., **100**, 061301 (2008)

Bergström, L., et al., arXiv:astro-ph/0609510v1 (2006).

Amelino-Camelia, G., et al., Nature, **393**, 319 (1998)

Biller, S.D., et al., Phys. Rev. Lett., **83**, 2108 (1999)

ABirkedal, A., et al., Phys. Rev. D., **74**, 035002 (2006).

Krauss, L.M., Nasri, S., Trodden, M., Phys. Rev. D, **67**, 085002 (2003).

Zee, A., Phys. Lett., **B93**, 339 (1980); Phys. Lett., **B161**, 141 (1985).

Baltz, E.A., and Bergström, L., Phys. Rev. D **67**, 043516 (2003).

Bringmann, T., Bergström, L., Edsjö, J., arXiv:hep-ph/0710.3169v1 (2007).

Ferrer, F., Krauss, L.M., Profumo, S., Phys. Rev. D., **74**, 115007 (2006)

Navarro, J. F., Frenk, C. S., & White, S. D. M. ApJ, **490**, 493 (1997).

Moore, B., Quinn, T., Governato, F., Stadel, J., & Lake, G. MNRAS, **310**, 1147 (1999).

Navarro, J.F., et al., MNRAS, **349**, 1039 (2004).

Diemand, J., et al., MNRAS, **364**, 665 (2005).

Strigari, L.E., et al., astro-ph/0611925 (2006).

Bergström, L., Ullio, P., Buckley, J.H., Astroparticle Physics, **9**, 137 (1998).

Kosack, K., et al., ApJ, **608**, L97 (2004).

Aharonian, F., et al., A&A**425**, L13–L17 (2004).

Horns, D., Physics Letters B, **607**, 225–232 (2005).

Profumo, S., Phys. Rev. D, **72**, 103521 (2005).

Stoehr, F., et al., MNRAS **345**, 1313 (2003)

P.D. Serpico and G. Zaharijas, 2008arXiv0802.3245S (2008)

Diemand, J., Kuhlen, M., Madau, P., Astrophys. J. **657**, 262 (2007)

Fornengo, N., Pieri, L., Scopel, S., Phys. Rev. D., **70**, 103529 (2004).

Vassiliev, V.V., 28th Int. Cosmic Ray Conf.(Tsukuba), 2679-2682 (2003).

LeBohec, S. L., & VERITAS Collaboration, 28th Int. Cosmic Ray Conf. (Tsukuba), 2521-2524 (2003).

Wood, M., et al., submitted (2007).

Aharonian, F., et al., Astropart. Phys., **29**, 55 (2008).

Baltz, E., et al., Phys. Rev. D, **61**, 023514 (2000).

Tyler, C., Phys. Rev. D, **66**, 023509 (2002).

Evans, N.W., Ferrer, F., Sarkar, S., Phys. Rev. D, **69**, 123501 (2004).

Bergström, L., Hooper, D., Phys. Rev. D, **73**, 063510 (2006).

Pieri, L., Branchini, E., Phys. Rev. D, **69**, 043512 (2006).

Strigari, L.E., et al. arXiv:0709.1510 [astro-ph].

Belokurov, V., et al., Astrophys. J., **654**, 897 (2007).

Martin, N.F., et al., MNRAS, **380**, 281 (2007).

Metz, M., Kroupa, P., MNRAS, **376**, 387 (2007).

Munoz, R.R., Majewski, S.R., Johnston, K.V., arXiv:0712.4312v1 [astro-ph] (2007).

Klypin, A., et al., Astrophys. J. **522**, 82 (1999).

Moore, B., et al., Astrophys. J., **524**, L19 (1999).

Carlson, E.D., Machacek, M.E., Hall, L.J., Astrophys. J., **398**, 43 (1992).

Spergel, D.N., Steinhardt, P.J., Phys. Rev. Lett., **84**, 3760 (2000).

Kaplinghat, M., Konx, L., Turner, M.S., Phys. Rev. Lett., **85**, 3335, (2000).

Kamionkowski, M., Liddle, A.R., Phys. Rev. Lett., **84**, 4525 (2000).

Zentner, A.R., Bullock, J.S., Phys. Rev. **D66**, 043003, (2002).

Dekel, A., Silk, J., Astrophys. J., **303**, 39 (1986).

Barkana, R., Loeb, A., Astrophys. J., **523**, 54, (1999).

Bullock, J.S., Kravtsov, A.V., Weinberg, D.H., Astrophys. J., **548**, 33, (2001).

Koushiappas, S.M., Zentner, A.R., Walker, T.P., Phys. Rev., **D69**, 043501, (2004).

Schmid, C., et al., Phys. Rev. D, **59**, 043517 (1999).

Hofmann, S., et al., Phys. Rev. D, **64**, 083507 (2001).

Chen, X., et al., Phys. Rev. D, **64**, 021302 (2001).

Berezinsky, V., et al., Phys. Rev. D, **68**, 103003 (2003).

Green, A.M., Hofmann, S., Schwarz, D.J., MNRAS, **353**, L23 (2004).

Green, A.M., et al., J. Cosmol. Astropart. Phys., **08**, 003, (2005).

Loeb, A., Zaldarriaga, M., Phys. Rev. D, **71**, 103520 (2005).

Bertschinger, E., Phys. Rev. D, **74**, 063509 (2006).

Moore, B., et al., astro-ph/0502213

Koushiappas, S.M., Phys. Rev. Lett., 97, 191301 (2006).

Peebles, P. J. E., Astrophys. J. **178**, 371 (1972).

Young, P., Astrophys. J. **242**, 1232 (1980).

Ipser, J.R., Sikivie, P., Phys. Rev. D **35**, 3695 (1997).

Quinlan, G.D., Hernquist, L., Sigurdsson, S., Astrophys. J. **440**, 554 (1995).

Gondolo, P., Silk, J., Phys. Rev. Lett. **83** 1719 (1999)

Merritt, D., Proceedings of Carnegie Observatories Centennial Symposium [arXiv:astro-ph/0301257].

Bertone, G., Merritt, D., Phys. Rev. D **72**, 103502 (2005)

Bertone, G., Merritt, D., Mod. Phys. Lett. A **20**, 1021 (2005)

Ullio, P., Zhao, H., M. Kamionkowski, M., Phys. Rev. D **64**, 043504 (2001)

Merritt, D., Milosavljevic, M., Verde, L., Jimenez, R., arXiv:astro-ph/0201376.

Merritt, D., arXiv:astro-ph/0301365.

Madau, P., Rees,M.J., Astrophys. J. Lett. **551**, L27 (2001).

Bertone, G., Zentner, A.R., Silk, J., Phys. Rev. D **72**, 103517 (2005).

Zhao, H.S., Silk, J., arXiv:astro-ph/0501625.

Islam, R., Taylor, J., Silk, J., MNRAS **354**, 443 (2003).

Islam, R., Taylor, J., Silk, J., MNRAS **354**, 427 (2004).

Koushiappas, S.M., Bullock, J.S., Dekel, A., MNRAS **354**, 292 (2004)

Edsjö, J., Schelke, M., Ullio, P., Journal of Cosmology and Astro-Particle Physics, **009**, 004-1–004-25 (2004).

Baltz, E.A., Gondolo, P., Phys. Rev. D, **67**, 063503-1–063503-8 (2003).

Bottino, A., Donato, F., Fornengo, N., Scopel, S., Phys. Rev. D, **68**, 043506-1 (2003)

Bottino, A., Donato, F., Fornengo, N., Scopel, S., Phys. Rev. D, **69**, 037302-1 (2004)

Griest, K., Kamionkowski, M., Phys. Rev. Lett., **64**, 615 (1990).

Profumo, S., Phys. Rev. D, **72**, 103521 (2005).

Tsuchiya, K., Enomoto, R., Ksenofontov, L. T., et al., ApJ 606, L115 (2004)..

Koushiappas, S., talk at "Ground-based Gamma-ray Astronomy: Towards the Future, May 11-12, Santa Fe (2006).

This 2-column preprint was prepared with the AAS LATEX macros v5.0.